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Physical modelling of pile-group effect on the local scour in submarine environments

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Abstract

Pile groups are extensively utilized to provide stability of offshore structures and bridges across rivers. Under the actions of waves and current, severe local scour can be induced around the pile groups in cohesionless soils, compromising the safety of structures significantly. An accurate prediction of local scour depth is difficult because the three-dimensional flow around pile groups is a complicated process. A series of flume tests were conducted in a novel water flume for flow-structure-soil interaction modelling, to investigate the local scour process around twin-pile groups. Two different hydrodynamic loading conditions, i.e., current alone and current plus waves, were adopted in the tests. The effects of the hydrodynamic loading conditions and the influence of the twin-pile layout on the scour have been investigated. It was found that compared with the maximum scour depths around a single pile, those around tandem twin-pile groups are generally a bit smaller while those around side-by-side twin-pile groups are remarkably larger, especially for the cases with small pile spacing. The observed maximum scour depth around side-by-side twin-pile groups with no separation can be nearly twice of that around a single pile. For the side-by-side arrangement, there is a qualitative agreement between the present results and the results of the preceding studies.

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Keywords: pile-group effect; local scour; physical modelling; current plus waves

1. Introduction

Pile groups are widely used in practice to support offshore structures (e.g. piers and jetties) and bridges across rivers. The safety of offshore piles in sand could be significantly compromised by waves/currents-induced scour [1].

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Nomenclature

d	seabed depth
d_{50}	median diameters of soil
D	pile diameter
D_r	relative density of soil
D_*	dimensionless grain size
e	void ratio of soil
Fr_a	average-velocity based Froude number
g	gravitational acceleration
G	(= G_0/D) pile spacing non-dimensionalized by pile diameter
G_0	pile spacing
h	water depth
H	wave height
KC	Keulegan-Carpenter number
Re	pile Reynolds number
S	maximum scour depth
S_0	maximum scour depth around a single pile
t	time
T	wave period
U_a	average water particle velocity during one-quarter cycle of oscillation under combined waves and current, when the oscillatory motion and the current are in the same direction
U_c	representative near-bed velocity of the current component of the undisturbed combined flow
U_f	maximum value of the undisturbed friction velocity
U_m	(= U_c+U_{wm}) maximum value of the combined waves and current velocity at the level of 1.0D above the sand-bed.
U_{wm}	maximum velocity of the undisturbed wave-induced oscillatory flow at the sea bottom above the wave boundary layer
α	flow skew angle
γ'	buoyant unit weight of soil
θ	Shields parameter
θ_{cr}	critical Shields parameter for sediment incipient motion
ρ_s	sediment grain density
ν	kinematic viscosity of water

As such, it is of great significance to understand the scour process around a group of vertical piles. While a substantial amount of knowledge has accumulated about scour around a single pile over the past half century [2], only a few studies have been conducted for scour at pile groups.

The assessment of the scour depth is essential in the design of both the foundation of the structure and the scour protection work. The scour around group of slender vertical piles in regular waves was investigated in laboratory tests by Sumer and Fredsøe [3]. The dimensions of the scour hole were found to be affected by the pile spacing and the flow skew angle. Field studies have been reported by Bayram and Larson [4] for wave scour around a group of vertical piles, which shows that the maximum scour depth has a distinct correlation with the Keulegan-Carpenter number. Liang et al. [5] investigated the scour around twin-pile groups subjected to oscillatory flows. The individual piles in a twin-pile groups were found to behave independently when the pile spacing was three times greater than the pile diameter. For the conditions of steady current, Ataie-Ashtiani and Beheshti [6] carried out 112 experiments covering different pile group arrangements, spacing and flow speed and a correction factor was derived to predict the maximum scour depth for the pile groups.

Scour around group piles under current plus waves is a common phenomenon in offshore environments. Few experimental studies have been found about this issue. In this paper, a series of flume tests were conducted in a novel water flume for flow-structure-soil interaction modelling, to investigate the local scour process around twin-pile groups. Two different hydrodynamic loading conditions, i.e., current alone and current plus waves, were adopted in the tests. The effects of the hydrodynamic loading conditions and the influence of the twin-pile layout on the scour are examined.

2. Flume experiments

2.1. Experimental set-up

The experiments were conducted in a flow-structure-soil interaction flume (52.0 m long, 1.0 m wide and 1.5 m high) at the Institute of Mechanics, Chinese Academy of Science. The flume can generate a constant flow and waves simultaneously. Experiment section (6.0 m long, 1.0 m wide and 2.0 m deep) is located in the middle of the flume. A saturated sand-bed was prepared to simulate a sandy seabed, which is 0.5 m thick. The main physical properties of sand-bed are listed in Table 1. The water depth (*h*) was kept constant at 0.5m, as illustrated in Fig. 1.

Far-field wave height was measured with a wave height gauge along the central line at the distance of 15 m apart from the front pile. An Acoustic Doppler Velocimetry (ADV) was mounted to measure the undisturbed flow velocity at the level of 1.0*D* above the sand-bed at the distance of 20 m apart from the front pile center. The scour depth evolution at upstream and downstream of each pile was monitored with four ultrasonic distance sensors (see Fig. 1).

Table 1. Index properties of test sands

Mean size of sand grains	Void ratio	Relative density	Buoyant unit weight of soil
d_{50} (mm)	e	D_r	γ' (kN/m^3)
0.15	0.35	0.62	10.65

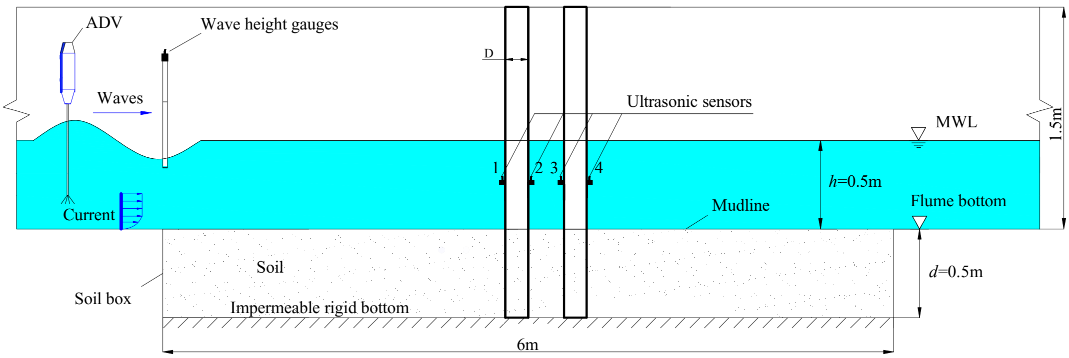

Fig. 1. Schematic diagram of the experimental system.

2.2. Test conditions

Two different sizes of model piles, *D*=12cm and *D*=8cm, were adopted in the tests. Various types of twin-pile layout are shown in Fig. 2. The flow skew angle α was varied between 0°, 30°, 60° and 90°. For the cases with a constant α, the pile spacing *G* was varied in an appropriate range. Note that large pile diameter (*D*=12cm) was adopted for α=0° and 30° while small pile diameter (*D*=8cm) was adopted for α=60° and 90°, to minimize the blockage effect. Two different hydrodynamic loading conditions, i.e., current alone and current plus waves, were adopted in the tests. Test conditions and scour measurements are summarized in Table 2 for current alone, and Table 3 for current with following waves. The wave parameters for the cases under current plus waves are *H*=0.14m and *T*=1.8s. As a reference, scour around a single pile was also examined. To obtain the value of S/S_0 for the twin-pile cases with *D*=8cm under current plus waves, the scour depth around a single pile (S_0) with D=8cm under the identical hydrodynamic condition was estimated based on the empirical prediction formula proposed by Qi and Gao [7].

The pile Reynolds number (Re) is defined as

$$\mathrm{Re}=U_m D/\nu \quad (1)$$

The average-velocity based Froude number (Fr_a) is defined as [7]

$$Fr_a = U_a / \sqrt{gD} \quad (2)$$

in which U_a ($=\frac{1}{T/4}\int_0^{T/4}\left(U_c+U_{wm}\sin(2\pi t/T)\right)dt = U_c+\frac{2}{\pi}U_{wm}$) is the average water particle velocity during one-quarter cycle of oscillation under combined waves and current, when the oscillatory motion and the current are in the same direction. The Keulegan-Carpenter number (KC) is defined as

$$KC=U_{wm}T/D \quad (3)$$

The Shields parameter (θ) is defined as

$$\theta = \frac{U_f^2}{g(\rho_s/\rho_w - 1)d_{50}} \quad (4)$$

The detailed calculation procedure of θ under combined waves and current is given by Soulsby [8]. The critical Shields parameter for the sediment initiation on the bed can be calculated by [8]

$$\theta_{cr} = \frac{0.3}{1+1.2D_*} + 0.055\left[1-\exp\left(-0.02D_*\right)\right] \quad (5)$$

For the present examined sand-bed the value of θ_{cr} is 0.058. As shown in Table 2 and 3, the clear-water scour regime prevailed for current alone conditions while the live-bed scour regime prevailed for the condition of current plus waves.

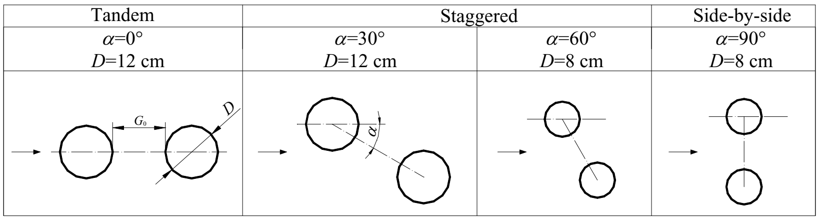

Fig. 2. Layout of twin piles of the tests

Table 2. Test results for local scour around pile groups: Current alone

Run number	Pile layout		D (cm)	U_c (m/s)	θ	Re	Fr	S (cm)	S/S_0
1	Single pile		12	0.23	0.043	2.76×10^4	0.212	8.0	1
2	Single pile		8	0.23	0.043	1.84×10^4	0.260	7.0	1
3	α=0°	G=0	12	0.23	0.043	2.76×10^4	0.212	6.8	0.85
4		G=1	12	0.23	0.043	2.76×10^4	0.212	8.6	1.08
5		G=3	12	0.23	0.043	2.76×10^4	0.212	6.8	0.85
6		G=5	12	0.23	0.043	2.76×10^4	0.212	7.0	0.88
7	α=30°	G=0	12	0.23	0.043	2.76×10^4	0.212	10.7	1.34
8		G=1	12	0.23	0.043	2.76×10^4	0.212	8.4	1.05
9		G=3	12	0.23	0.043	2.76×10^4	0.212	8.5	1.06
10		G=0	8	0.23	0.043	1.84×10^4	0.260	9.0	1.29
11	α=60°	G=0	8	0.23	0.043	1.84×10^4	0.260	11.2	1.60
12		G=1	8	0.23	0.043	1.84×10^4	0.260	8.3	1.19
13		G=3	8	0.23	0.043	1.84×10^4	0.260	8.2	1.17
14	α=90°	G=0	8	0.23	0.043	1.84×10^4	0.260	12.5	1.78
15		G=1	8	0.23	0.043	1.84×10^4	0.260	9.0	1.29
16		G=3	8	0.23	0.043	1.84×10^4	0.260	7.5	1.07

Table 3. Test results for local scour around pile groups: Current plus waves

Run number	Pile layout		D (cm)	U_c (m/s)	U_{wm} (m/s)	θ	KC	Re	Fr_a	S (cm)	S/S_0
17	Single pile		12	0.23	0.25	0.270	3.75	2.76×10^4	0.359	9.8	1
18	α=0°	G=0	12	0.23	0.25	0.270	3.75	2.76×10^4	0.359	9.2	0.94
19		G=1	12	0.23	0.25	0.270	3.75	2.76×10^4	0.359	9.5	0.97
20		G=3	12	0.23	0.25	0.270	3.75	2.76×10^4	0.359	8.5	0.87
21		G=5	12	0.23	0.25	0.270	3.75	2.76×10^4	0.359	9.0	0.92
22	α=30°	G=0	12	0.23	0.25	0.270	3.75	2.76×10^4	0.359	13.2	1.35
23		G=1	12	0.23	0.25	0.270	3.75	2.76×10^4	0.359	10.2	1.04
24		G=3	12	0.23	0.25	0.270	3.75	2.76×10^4	0.359	10.0	1.02
25		G=0	8	0.23	0.25	0.270	5.63	1.84×10^4	0.440	12.3	1.67
26	α=60°	G=0	8	0.23	0.25	0.270	5.63	1.84×10^4	0.440	14.0	1.91
27		G=1	8	0.23	0.25	0.270	5.63	1.84×10^4	0.440	11.0	1.50
28		G=3	8	0.23	0.25	0.270	5.63	1.84×10^4	0.440	8.5	1.16
29	α=90°	G=0	8	0.23	0.25	0.270	5.63	1.84×10^4	0.440	15.2	2.07
30		G=1	8	0.23	0.25	0.270	5.63	1.84×10^4	0.440	12.0	1.63
31		G=3	8	0.23	0.25	0.270	5.63	1.84×10^4	0.440	7.8	1.06

2.3. Testing procedure

In general, the testing procedure was adopted as follows:

(1) The flume including the soil box was firstly emptied and cleaned. The soil box was whereafter filled with clean water to a certain depth. The sand bed was carefully prepared by means of sand-raining technique. The surface of the sand bed was leveled off smoothly with a scraper.
(2) The flume was then filled slowly with water to a given depth (e.g. 0.5 m).
(3) Both the wave maker and the current generator were switched on to generate waves and current concurrently.
(4) The multichannel synchronous sampling system was then started to measure the multi-physics parameters, e.g. wave height, flow velocity, and scour depth.

3. Results and discussions

3.1. Effects of pile spacing on scour process

Fig. 3(a) and (b) give two series of scour depth developments at the upstream edge of the front model pile under current alone and current plus waves for D=12 cm and α=0º (tandem), respectively, showing the effect of pile spacing. It is indicated that the scour depths for all the cases in Fig. 3 experience a rapid increase at the beginning. In spite of the significant reduction of increasing rate of the scour depth, none of the tests have reached equilibrium till the end of the tests. Sheppard et al. [9] applied a four-parameter exponential function for extrapolation of the maximum scour depth (S) from scour depth development versus time (t). We have adopted this function for extrapolation of S_t (scour depth corresponding to t) as a function of t to obtain S. It is noticed that the ratio of the extrapolated and observed maximum scour depth was less than 1.2 for most examined cases. In the following analysis, the observed maximum scour depth at time t=120 min was used as S instead of the extrapolated one.

Fig. 3 shows that the pile spacing has slight effect on the maximum scour depth for the tandem arrangement under either current alone or current plus waves. This could be explained by the fact that the horseshoe vortex in front of the pile is the controlling mechanism of the local scour, which is generally independent with the rear pile. It is noticed that for the cases with relatively small spacing (i.e. G=0 and 1) in Fig. 3(a), the scour depths increase more tardily compared with the cases of single pile and with relatively large spacing (i.e. G=3 and 5). This should be attributed to the enlarged dimension of the scour hole along the flow direction for the cases with G=0 and 1. Due to the relatively small spacing, two local scour holes around the front pile and the rear pile merged into one and the path for a soil particle to move out of the merged scour hole became longer, rendering the development of the scour hole relatively slow.

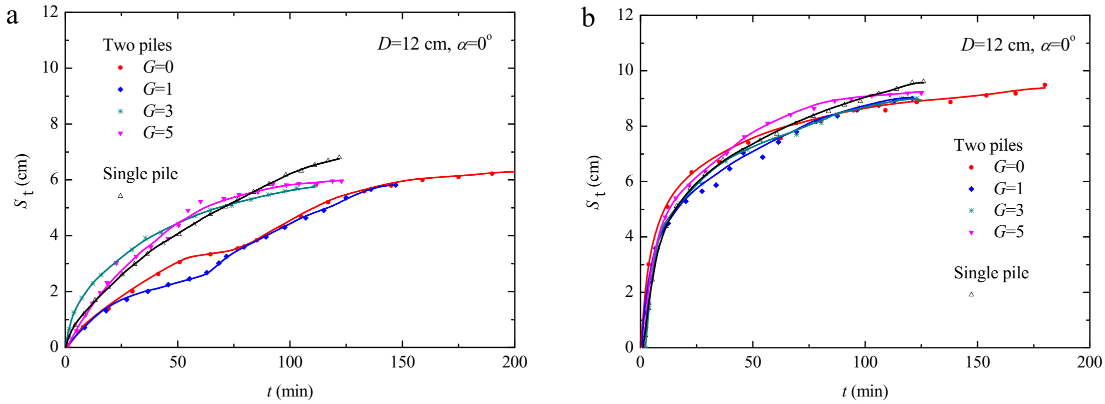

Fig. 3. Time development of scour depth measured at upstream edge of the front pile with various pile spacings for tandem arrangement: (a) current alone, runs 1 & 3-6; (b) current plus waves, runs 17-21.

The development of scour depth with various pile spacings for staggered arrangement are shown in Fig. 4. The pile diameter adopted in the cases with α=30° is D=12cm while in the cases with α=60° is D=8cm to eliminate the blockage effect. In contrast to the cases with tandem arrangement, the rate of scour depth for staggered cases with G=0 is remarkably faster than that for single pile. Nevertheless, the rate of scour depth for G=1 and 3 is generally consistent with and even slightly slower than that for single pile. The effects of pile spacing on the development of scour depth are the same for the cases with current alone and cases with current plus waves.

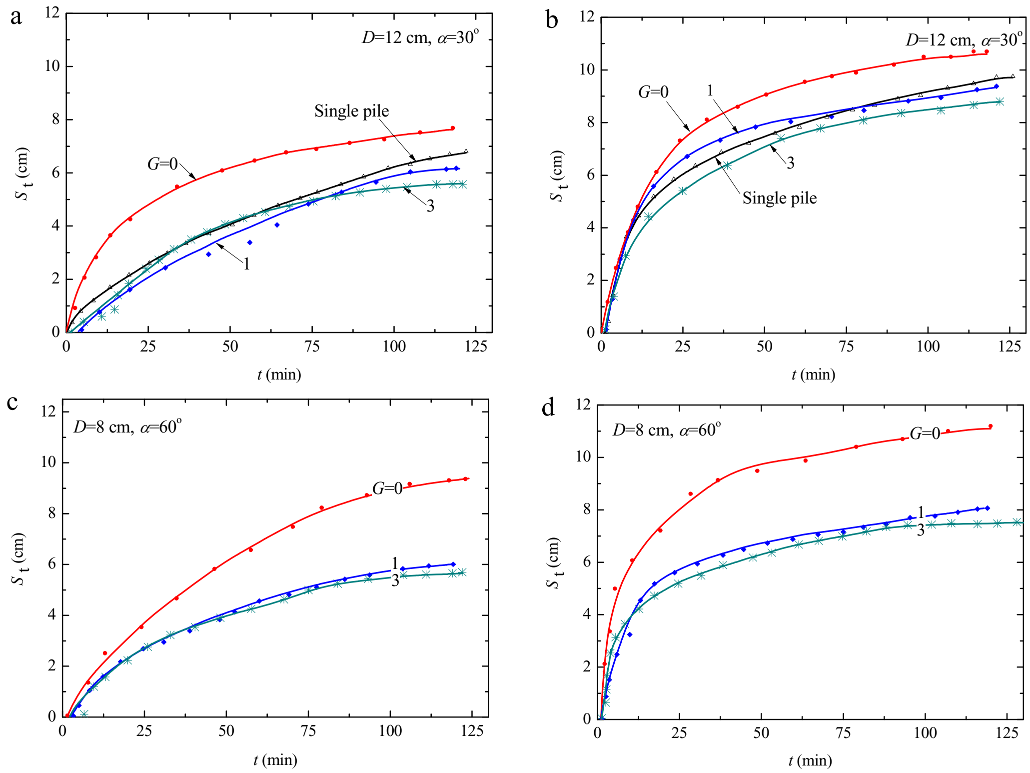

Fig. 4. Time development of scour depth measured at upstream edge of the front pile with various pile spacings for staggered arrangement: (a) current alone, runs 1 & 7-9; (b) current plus waves, runs 17 & 22-24; (c) current alone, runs 11-13; (d) current plus waves, runs 26-28.

For the side-by-side arrangement, the effects of pile spacing is significant, as shown in Fig. 5. Under current alone, the initial stage of the scour depth development with a rapid increasing rate is not very much influenced by the pile spacing, whilst the development curves exhibit observable difference in the next section. Under current plus waves, the whole curves of scour depth development are distinguishable for different spacings. As the spacing increases, the pile group effect gradually reduces.

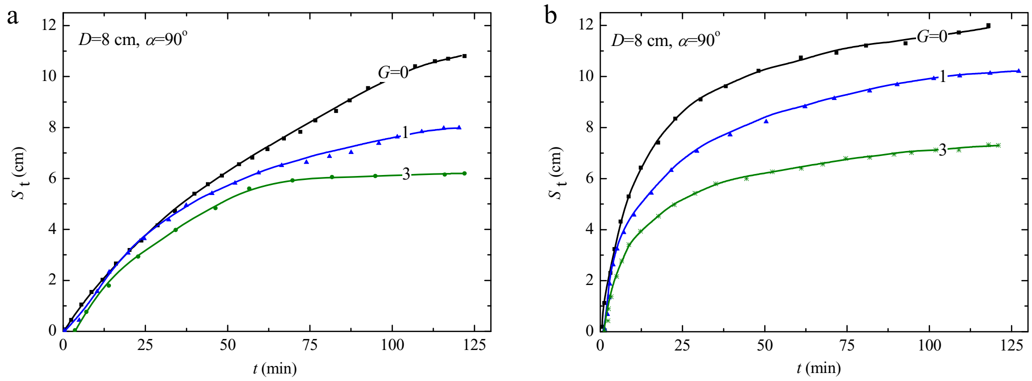

Fig. 5. Time development of scour depth measured at upstream edge of the front pile with various pile spacings for side-by-side arrangement: (a) current alone, runs 14-16; (b) current plus waves, runs 29-31.

3.2. Effects of flow skew angle on scour process

The controlling mechanism for local scour around piles is the three-dimensional vortex induced by pile-current/wave interaction. For group piles, the vortices around each single pile interacts with each other and thus change the scour development around the piles. Besides the pile spacing, the flow skew angle is the other crucial parameter for determining the scour development around pile groups.

Fig. 6(a) and (b) give two series of scour depth developments at the upstream edge of the front model pile for D=8 cm and G=0 under current alone and current plus waves, respectively. Under current alone, both the scouring rate at the initial stage and the equilibrium scour depth are remarkably enhanced as the flow skew angle increases, which would be attributed to the enhanced horseshoe vortex resulted from the increasing projected width of the piles onto a plane normal to the flow. Under the conditions of current plus waves, the equilibrium scour depth is obviously increased by increasing flow skew angle, while the scouring rate at the initial stage seems to be little influenced. A comparison between Fig. 6(a) and (b) indicates that, the effect of flow skew angle under which the live-bed condition prevails (see Fig. 6(b)) is not as obvious as that under which the clear-water condition prevails (see Fig. 6(a)).

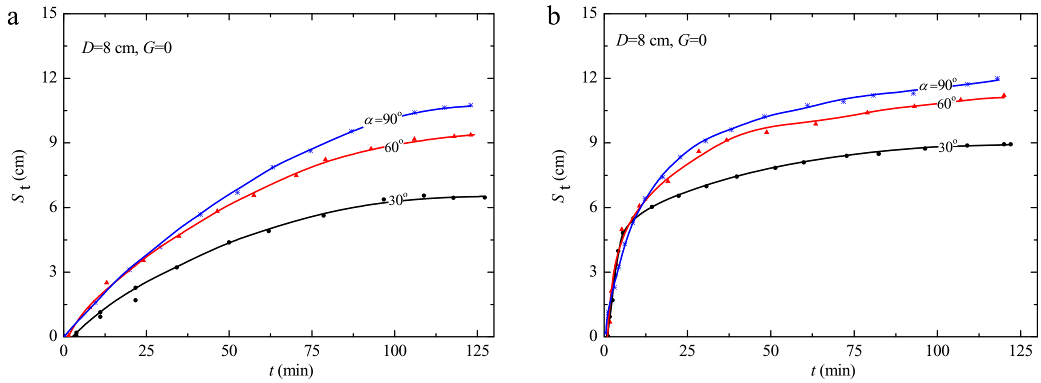

Fig. 6. Time development of scour depth measured at upstream edge of the front pile with various orientations: (a) current alone, runs 10, 11, 14; (b) current plus waves, runs 25, 26, 29.

3.3. Pile group effect on scour depth

The variations of the present measured scour depths with pile spacing under different flow skew angle are plotted in Fig. 7. It can be seen that the variation trend of S/S_0 with G under current alone is generally consistent with that under current plus waves. This consistency is beneficial to the conclusion that the pile group effect is independent with the hydrodynamic loading condition.

Fig. 7 shows that large flow skew angle helps to enhance the pile group effect. The value of S/S_0 can be up to approximately 2.0 for the condition of α=90° and G=0. For the cases with α=0°, S/S_0 gradually increases with the increasing of the spacing until G=1 and then reduces with increasing G. It should be noted that the value of S/S_0 is by and large smaller than 1.0 for the cases with α=0°, indicating that the pile group effect could reduce the scour depth under the present conditions. For the cases with α>30°, S/S_0 decreases with increasing spacing to a certain value of S/S_0=1.0, and then remains reasonably constant for further increase in G.

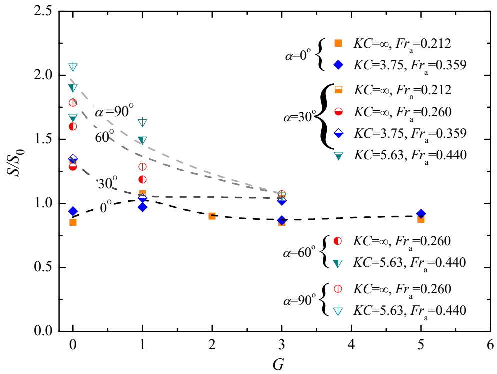

Fig. 7. Variation of S/S_0 with pile spacing.

Fig. 8 gives the comparison of the maximum scour depth between the present measured data and the existing experimental data. It can be seen from Fig .8(a) that for the tandem pile arrangement (α=0°), the holistic variation trends of S/S_0 with G are the same in spite of different incipient flow and soil conditions. Nevertheless, the specific values of S/S_0 hold considerable deviation between different tests.

For the side-by-side arrangement (α=90°), there is a general and qualitative agreement between the present results and the results of the preceding studies. The pile group effect is obvious for G<3 and gradually vanishes for G>3. In the practical offshore environments, the flow skew angle could be diverse and thus the upper envelope of S/S_0 with G under different values of α, as shown in Fig. 8(b), is of great significance.

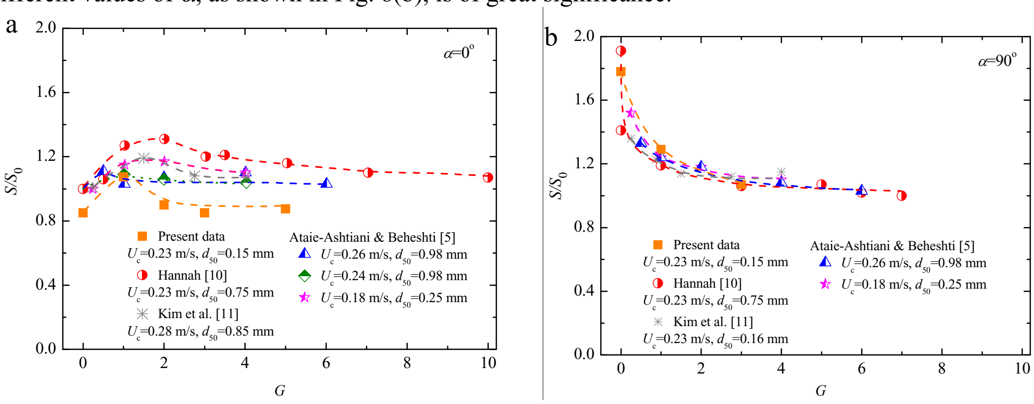

Fig. 8. Comparison of the maximum scour depth between the present measured data and the existing experimental data: (a) α=0°; (b) α=90°.

4. Conclusions

Local scour was investigated for twin pile groups by conducting a series of flume tests in a water flume. The effects of pile spacing on the time development of scour depth around twin pile groups are much more significant for staggered and side-by-side arrangements compared with tandem arrangement. The maximum scour depth is remarkably enhanced as the flow skew angle increases. The effect of flow skew angle under live-bed condition is not as obvious as that under clear-water condition. The observed maximum scour depth around side-by-side twin pile groups with no separation can be nearly two times of that around a single pile. The pile group effect is obvious for $G<3$ and gradually vanishes for $G>3$. For the side-by-side arrangement, there is a qualitative agreement between the present results and the results of the preceding studies, in spite of different hydrodynamic loading conditions and soil conditions. This consistent upper envelope of S/S_0 with G under different flow skew angles is of great significance considering the diverse flow skew angle in the practical offshore environments.

Acknowledgements

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